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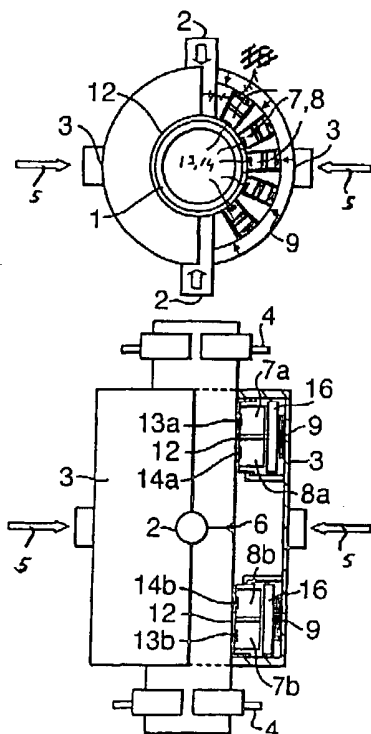
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[Continued on next page]

(54) Title: ELECTROMAGNETIC ACOUSTIC TRANSDUCER (EMAT) WELD INSPECTION



(57) Abstract: A method and an assembly for inspecting welds between welded tubular ends comprises arranging a series electromagnetic acoustic transducer (EMAT) (7a, 8a, 7b, 8b) assemblies in circumferential direction adjacent to an inner and/or outer surface of at least one of the welded tubular ends and inducing the EMAT assemblies to transmit sequentially or simultaneously acoustic shear wave signals towards the weld and to detect the shear waves reflected by and/or passing through the weld while the EMAT assemblies are maintained in a substantially fixed position relative to the weld such that at least a substantial part of the weld is scanned by the EMAT assemblies instantly after the weld is made.

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## ELECTROMAGNETIC ACOUSTIC TRANSDUCER (EMAT) WELD INSPECTION

**Background of the invention**

The invention relates to a method and system for inspecting welds by means of an Electro Magnetic Acoustic Transducer (EMAT) assembly.

5       The use of EMAT assemblies for inspecting welds is known from US patents 5,439,157 and 5,474,225. In the known EMAT weld inspection methods a robotic transport apparatus containing EMAT transmitting and receiving coils is automatically positioned at one side of a  
10       just-completed weld whereupon the EMAT transmitting coil transmits ultrasonic SH shear waves towards the weld and the EMAT receiving coil transduces any ultrasonic SH shear waves reflected by the weld in a signal which is used to signal the presence of defects in the weld on the  
15       basis of the received signal. The robotic transport apparatus is in use moved along the surface of one of the welded plates parallel to the weld and may be connected to a control unit which automatically adjusts the settings of the welding apparatus which moves ahead of  
20       the EMAT weld assembly. The use of a robotic transport apparatus is not practical for inspection of welds between tubulars since it requires the robotic transport apparatus to rotate around a welded tubular, which is time consuming and requires the use of a fragile robotic  
25       tool.

The use of EMAT devices for weld and/or pipe inspection is also disclosed in  
US Patent No. 5,652,389 to Barnes, et. al.,  
US Patent No. 5,760,307 to Latimer et. al.,

WO Patent No. 02/40986 and US patent 5,808,202  
to Passarelli. Barnes discloses a pulse-echo technique  
and apparatus for inspection of inertia welds in  
plat-plates using EMAT. Latimer discloses a method to  
5 eliminate root and crown signals using crossed or  
collinear EMATs, and Passarelli discloses a pulse-echo  
technique for the inspection of cylindrical objects  
including rods and tubes.

The device disclosed by Passarelli has the  
10 disadvantage that it is has a fixed ring-shape  
construction, which cannot be put readily around the  
tubulars and the weld at the rig floor without the danger  
of damaging the device or at the expense of substantial  
time delays. Another disadvantage to this arrangement is  
15 the geometry of the electromagnets, the transmitter and  
the receiver coil, which does not provide a  
100% inspection of the weld around the circumference of  
the pipe, as the aperture of the transmitters is smaller  
than the ultrasonic field at the weld region. Rotating  
20 the tubular could mitigate the disadvantage, but that is  
not possible when the tubulars are welded at the rig  
floor, as will be explained below. An additional,  
difficulty posed by this and other prior art is that the  
weld is inspected by pulse-echo reflection measurement  
25 only. However, to prevent miss-interpretation of the  
reflected signals, e.g. due to diffraction or scatter at  
the weld, it is preferred to measure both reflection and  
transmission at the same time using at least two EMATs  
positioned upstream and downstream from the weld.

30 It is an object of the present invention to provide  
an improved method and system for inspecting welds by  
means of an EMAT assembly which does not require the use  
of robotic transport apparatus and which can be activated

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to inspect the weld on any irregularities and/or the presence of oxide inclusions instantly after the weld is made throughout the length of the weld.

Summary of the Invention

5           The tubular weld inspection method according to the invention comprises arranging a series of electromagnetic acoustic transducer (EMAT) assemblies in circumferential direction adjacent to an inner and/or outer surface of at least one of the welded tubular ends and inducing the  
10       EMAT assemblies to transmit sequentially (ie. individually or grouped) or simultaneously acoustic shear wave signals in different modes and angles towards the weld and to detect the shear waves reflected by and/or passing through the weld such that at least a  
15       substantial part of the weld is scanned by the EMAT assemblies and wherein the EMAT assemblies are maintained at a substantially fixed position relative to the weld during the scanning operation.

          It is observed that the use of EMAT assemblies that  
20       are maintained at a substantially fixed position relative to the weld during the scanning operation enables instant weld inspection after the weld has been made and thus enables significantly faster weld inspection that with currently known EMAT inspection tools where the EMAT  
25       assemblies are moved relative to the weld during the weld scanning process as disclosed in US patent 4,184,374; US patent 5,085,082 and International patent application WO96/02831.

          Optionally, the EMAT assemblies comprise a ring  
30       shaped assembly of circumferentially spaced EMAT transmitters and a ring shaped assembly of circumferentially spaced EMAT receivers, which is

arranged between the weld and the ring shaped assembly of EMAT transmitters.

5 In a preferred embodiment the EMAT assemblies comprise ring shaped assemblies of EMAT transmitter and receiver assemblies at both sides of the weld when seen in longitudinal direction of the welded tubulars.

10 It is preferred that each of the EMAT transmitter and receiver assemblies comprises a matrix of EMAT transducers which at least partly overlap each other in a circumferential direction so that the entire length of the weld can be inspected instantly after the welding operation by a stationary array of EMAT transmitters which each transmit shear waves into a segment of the pipe wall that tends to be narrower than the width of the EMAT transmitter itself.

15 The EMAT transducers of at least one matrix may be stacked on top of each other in a radial direction relative to the tube wall. Alternatively, the EMAT transducers of at least one matrix are staggered in a substantially longitudinal direction relative to the tube wall.

20 In one embodiment the EMAT assembly is arranged on a carrier body, which is arranged in the interior of at least one of the welded tubulars. This embodiment of the EMAT assembly can also be used for inspection of welds in-situ, e.g. downhole, or in laying barge pipelines, either immediately after welding or some time later, e.g. to inspect the quality of the welds after several years service.

30 In an alternative embodiment the EMAT assembly is arranged on a carrier sleeve which surrounds at least one of the welded tubulars and which can optionally be split into at least two sleeve segments after completion of the

welding operation. This embodiment can also be used for inspection of welds in-situ, e.g. at the rig floor or in laying barge pipelines.

5 The EMAT tubular weld inspection method and assembly is able to inspect the quality of forge welded tubulars instantly after the forge weld has been made.

10 The EMAT assembly according to the invention comprises a series of electromagnetic acoustic transducers which are in use distributed in a circumferential direction adjacent to an inner and/or outer surface of at least one of the welded tubular ends and are configured to transmit sequentially or simultaneously acoustic shear wave signals in different modes and angles towards the weld and to detect the shear waves reflected by and/or passing through the weld such that at least a substantial part of the weld is scanned by the EMAT assembly.

15 In an embodiment, the assembly comprises at least two longitudinally spaced ring shaped arrays of EMAT transmitters and receivers such that the ring shaped arrays of EMAT receivers are located between the ring shaped arrays of EMAT transmitters.

#### Description of preferred embodiments

25 Some preferred embodiments of the EMAT weld inspection method and assembly according to the invention will be described in more detail with reference to the accompanying drawings, in which:

30 Figures 1a and 1b show side and top views of a forge welding apparatus which is equipped with an EMAT weld inspection assembly according to the invention.

Fig.2 shows a longitudinal section view of a spear which is inserted into a pair of forge welded tubulars

and which carries ring shaped assemblies of EMAT transmitters and receivers at each side of the weld;

Fig.3 shows a longitudinal sectional view of a weld between tubulars through which an ultrasonic signal is transmitted;

Fig.4a-e show a three-dimensional view of an EMAT transmitter and receiver assembly and how the acoustic signal is transmitted into the tubular wall; and

Fig.5 shows various suitable configurations of the EMAT transmitter and receiver assemblies.

The traditional method of connecting lengths of OCTG (Oil Country Tubular Goods), whether they are for downhole casing or tubing, is to use a threaded connection or another form of joining based on a suitable welding technique like explosive welding, shielded active gas welding, flash butt welding, etc.

In the case of welding, the presence of certain defects will reduce the strength and thus the safety and structural integrity of the downhole oil or gas tubular. Therefore, proper inspection of the weld for flaws or other irregularities is mandatory. It is preferred to inspect the weld immediately after the weld is made using a non-destructive test technique.

At the rig-floor the tubulars 1 are kept aligned in an upright and fixed position during welding using pipe grippers 4 as shown in Fig 1 and 2. After inspection and approval of the weld quality the tubular 1 is lowered in to the wellbore, and another piece of tubing or casing (minimal length 10 meters) is positioned on top of it and welded, etc. To minimise the loss of rig-time and to enhance safety at the rig-floor, it is preferred to perform the inspection of the weld in a fully automatic way, starting immediately after the weld is made and



completed in a minimum of time. For well integrity reasons it is mandatory to inspect the weld over its full length along the circumference of the pipe.

At present, a range of well known technologies are available for inspection of butt welds in tubes and pipes, based on x-ray, ultrasonic inspection techniques, EMAT, eddy current inspection and their derivative techniques as SLOFEC, remote field eddy current, partial saturated eddy current, etc.

However, the requirement for inspection of tubulars intended for use in downhole environments presents novel challenges that disqualify many techniques and/or configurations. These are requirements for:

- a. rapid completion of testing on relatively poorly prepared surfaces, with the weld still hot.
- b. fully automatic operation of the testing equipment.
- c. immediate feedback to allow assessment for acceptance or rejection of the weld.
- d. integration with the welding device
- e. safe operation in a potentially hazardous environment.

The present invention enables the use of EMAT weld inspection technology at the rig-floor.

EMAT (electromagnetic acoustic transducer) inspection is a known inspection technique, in which interaction between a magnetic and electromagnetic field induces acoustic energy in the test piece. The generated acoustic wave is reflected by anomalies or defects and can be detected by a suitable receiver. The receiver can be either a conventional piezo-electric transducer or an EMAT. To validate the magnetic coupling of the transmitting EMAT a receiver on the other side of the weld can be applied as a transmission check.

In this case the relative strength of this energy is altered by the presence of defects and is used to identify defects.

In the method according to the invention novel transmission and receiver EMAT assemblies are used which are maintained in a stationary position relative to the weld and are suited to inspection of forge-welded pipes instantly after the forge welding operation. To ensure correct and accurate positioning of the EMAT probes, a novel design has been made where stationary EMAT assemblies are configured to scan the entire length of the weld that allows integration into the forge-welding machine or into the internal spear used for the alignment of the tubulars while welded together.

Reference is now made to Figures 1 and 2, which depict an external non-destructive weld testing apparatus comprising two EMAT probes 7,8. It is preferred that the EMAT probes 7,8 are positioned either above the weld 6, below the weld 6 or, preferably, above and below the weld 6 and that they are in close proximity (typically no more than 2 mm from) the pipe wall. Each EMAT probe comprises a series of circumferentially distributed EMAT transmitter and receiver assemblies 7a, 7b, 8a, 8b. In each assembly the receiver 8a, 8b is positioned adjacent to the transmitter 7a, 7b but between the transmitter 8a, 8b and the weld 6. The stationary EMAT probes can be integrated into the external gas shield chamber 3 of the forge-welding machine (Fig.1) or into the internal spear 25 (Fig.2).

The stationary EMAT probe 7, 8 is ring-shaped as shown in Fig. 1a and 1b and is segmented into at least two parts as illustrated in Fig. 1a. During the whole welding and inspection operation, the pipes 1 are kept in

a fixed position, they cannot rotate, using pipe grippers 4. The gas shield chamber 3 of the forge-welding machine is closed during that time and surrounds the electrodes 2 that are pressed against the pipes 1 before the forge operation to heat the pipe ends that are to be forge welded together.

Control electronics, pre-amplifiers, signal pre-processors etc. are located close to the electromagnets and the EMAT transmitter and receiver coils T/R in printed circuits 16. Active cooling for the electromagnets is also provided by flushing shield gas into the chamber 3, as illustrated by arrows 5.

In use, each R/T pair 8a, 7a, 8b, 7b is activated and controlled by an electronic switch box in printed circuit 16. A signal is generated by each of the transmitters 7a, 7b, etc. and transmitted via the pipe 1 toward the weld 6, the adjacent receiver 8 detects this signal for calibration purposes and the signal continues to propagate toward the weld 6. If there is a defect in the weld 6 then the signal is reflected back toward the transmitter 7a, 7b whereupon the receiver 8a, 8b will detect it and report a defect.

When applied together with the forge-welding machine as illustrated in Fig. 1a and b the EMAT probes 7, 8 are automatically centred around the pipe wall 1, using a spring system 9, when the gas shield chamber 3 is closed. The surfaces 13a-b, 14a-b of the EMAT transmitters and receivers 7a-b, 8a-b are protected by a thin film 12, typically a 0.1mm metal thick metal film although other wear resistant materials can be employed.

Fig. 2 depicts EMAT probes which are mounted on an internal spear 25 for e.g. forge welding. In this application the EMAT inspection probes 7, 8 comprise a

series of circumferentially spaced pairs of EMAT transmitters 7c and 7d and EMAT receivers 8c, 8d at each side of the weld area 6. Provision is made in the spear 25 for the permanent or electromagnets required for EMAT inspection and a suitable power supply, electronic switching box and data umbilical is provided.

The simplest and preferred embodiment requires that the spear 25 is pre-positioned in one of the pipes 1 to be welded. This allows inspection probes to be in good contact with the pipe wall without a drift requirement and can be accomplished by using a simple backing material such as a foam rubber. Where the inspection device needs to be drifted into position then the EMAT probe assemblies 7c-d, 8c-d are positioned against the pipe 1 using an activation method of which there are several possibilities.

The EMAT probe assemblies 7, 8 are stand-by during the welding operation and start the inspection immediately after the welding process is completed and the local temperature of the weld is low enough, e.g. 700 °C.

An almost identical configuration can be used in a pipe inspection pig or logging device for inspection of welds in-situ, e.g. downhole or in pipelines at or near the earth surface to inspect the quality of the welds after several years service.

Figure 3 illustrates the benefits of the use of a second series of EMAT receivers e.g. R2 on the opposite side of the weld 6 to the transmitters, e.g. T1 in addition to the conventional use of a first series of EMAT receivers R1 at the same side of the weld 6 as the transmitters T1. In the event that there is no defect present in the weld 6 this second series of matching

receivers R2 will detect a strong signal when the signal has passed through the weld. If this second series of receivers R2 is not present then a larger degree of uncertainty exists with regard to defect sizing because reflected signals may scatter and be lost, in which case the size of a defect in the weld 6 may be incorrectly/misleadingly reported.

Besides validation, the symmetrical configuration of transmitters and receivers T1,2 and R1,2 at both sides of the weld 6 provides means for gain control of the receiving coil e.g. R1. A further advantage of the symmetrical transmitter and receiver configuration T1,2 and R1,2 is that it enables the EMAT system to be operated in different modes. For example, by altering the relative angle between the pipe, magnetic and electromagnetic field it is possible to cause the steel to vibrate in just any direction. One of the advantages of this is that it allows the full body of the pipe wall to be "vibrated" and for the full body vibration to travel along the pipe parallel to the pipe wall. This prevents 'skipping' as indicated in Fig. 3 and improves the signal-to-noise ratio significantly. The same process is repeated for transmitter T2 thus giving redundancy to the entire configuration.

Reference is made to Figure 4a and b, which depict EMAT transducer and receiver probes 7,8 that are composed of a set of laminated electromagnets 17 which can be controlled individually, in groups or all at the same time. The individual electromagnets 17 are separated from each other by a thin spacer 18. In the preferred embodiment illustrated in Fig. 4b the individual electromagnets 17 can be put together with legoland type connections 17a. This construction enables the EMAT probe

assemblies 7,8 to be re-configured for different pipe diameters. The ends of the EMAT probes 7,8 are covered with a suitable face protection material 15, e.g. Vespel, to prevent damaging and fouling of the transducer and receiver assemblies. At this location (on both sides) the flexible transducer and receiver coils 13a, 14a can move freely to adapt to diameter changes. The EMAT probe assemblies 7,8 are separated by means of another dielectric spacer 11. The transducer and receiver coils 13a, 14a are placed inside a recessed area or at the surface of the electromagnet elements.

Reference is made to Figure 4c. An electrostatic shield 22 is used to safeguard the EMAT receiver coil 14 from the effects of undesirable electric interference. The electrostatic shield, e.g. mu-metal, grounded, acts as a barrier to protect the EMAT receiver coil 14 from electrostatic interference and radio frequency interference (EMI/RFI).

Reference is made to Figure 4d and 4e. Here the means are disclosed by whom to create a focal area (aperture) of the ultrasonic wave 21 that has an identical size as one or more of the electromagnet elements 17. One or more (could even be all) electromagnet elements 17 can be magnetised thus forming a larger magnetic field than from one single electromagnet element 17. The electromagnet elements 17 can be switched on and off individually, in groups or all at the same time, using the control electronics in an electric current 16 as illustrated in Fig. 1.

Reference is made to Figure 5. Using novel design, use and control of meander-loop coils elements 23 provide the option to select different modes of operation and transmission angles of the ultrasonic wave, allowing a

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full inspection of the entire weld all around the circumference of the pipe.

Within the ring of electromagnets a transmitting or receiving coil 13, 14 is present as illustrated in Fig. 5a, which can be a length of wire or build up out of separate meander-loop coil elements as illustrated in Fig. 5b. The transmitting or receiving coil elements 13,14 can be controlled separately to obtain either one large meander-loop as shown in Fig. 5c or a phased array to generate an angled ultrasonic wave as shown in Fig. 5d. The receiver coil elements 23 are equipped with suitable pre-amplifiers 24. They can be processed separately or combined using the control electronics in 16.

Furthermore, by introducing small coil elements 23 a number of additional different configurations illustrated in Fig, 5e, 5f, 5g, 5h can be created for different inspection purposes.

Basic configurations are:

- (I) a long meander loop coil (i.e. circumferential direction) as illustrated in Fig. 5f,
- (II) a short meander loop coil (i.e. radial direction) using a single layer of coils as illustrated in Fig. 5g.
- (III) two or more staggered layers as illustrated in Fig. 5h of can be used to create an improved coverage, additional depth direction and better signal-to-noise ratio. The overall thickness of the staggered layers should be small, in the order of 1 mm.

Variations are possible.

The preferred embodiment is accomplished by sandwiching two or more layers of flexible probe around the full circumference of the pipe. An alternative embodiment would have the layers of EMAT probes

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positioned in a similar staggered pattern but with one layer above the other. Preferably the transmitter and receiver coils are put on a flexible carrier or substrate, which can be exchanged readily at the rig-floor.

5



C L A I M S

1. A method for inspecting welds between welded tubular ends, the method comprising arranging a series of electromagnetic acoustic transducer (EMAT) assemblies in circumferential direction adjacent to an inner and/or outer surface of at least one of the welded tubular ends and inducing the EMAT assemblies to transmit sequentially or simultaneously acoustic shear wave signals in different modes and angles towards the weld and to detect the shear waves reflected by and/or passing through the weld such that at least a substantial part of the weld is scanned by the EMAT assemblies and wherein the EMAT assemblies are maintained at a substantially fixed position relative to the weld during the scanning operation.

2. The method of claim 1, wherein the EMAT assemblies comprise a ring shaped assembly of EMAT transmitters and a ring shaped assembly of EMAT receivers, which is arranged between the weld and the ring shaped assembly of EMAT transmitters.

3. The method of claim 2, wherein the EMAT assemblies comprise ring shaped assemblies of EMAT transmitter and receiver assemblies at both sides of the weld when seen in longitudinal direction of the welded tubulars.

4. The method of claim 2 or 3, wherein each of the EMAT transmitter and receiver assemblies comprises a matrix of EMAT transducers which at least partly overlap each other in a circumferential direction.

5. The method of claim 4, wherein the EMAT transducers of at least one matrix are stacked on top of each other

in a partially overlapping pattern in a radial direction relative to the tube wall.

5 6. The method of claim 4, wherein the EMAT transducers of at least one matrix are staggered in a substantially longitudinal direction relative to the tube wall.

7. The method of any preceding claim wherein the EMAT assembly is arranged on a carrier body which is arranged in the interior of at least one of the welded tubulars.

10 8. The method of any one of claims 1-6, wherein the EMAT assemblies are arranged on a carrier sleeve which surrounds at least one of the welded tubulars and which can optionally be split into at least two sleeve segments after completion of the welding operation.

15 9. The method of any preceding claim, wherein the EMAT assemblies are operated to inspect the quality of forge welded tubulars instantly after the forge weld has been made.

20 10. An EMAT assembly for inspecting welds between welded tubular ends, the assembly comprising a series of electromagnetic acoustic transducers which are in use distributed in a circumferential direction adjacent to an inner and/or outer surface of at least one of the welded tubular ends and are configured to transmit sequentially or simultaneously acoustic shear wave signals in  
25 different modes and angles towards the weld and to detect the shear waves reflected by and/or passing through the weld such that at least a substantial part of the weld is scanned by the EMAT assembly .

11. The EMAT assembly of claim 10, wherein the assembly comprises at least two longitudinally spaced ring shaped arrays of EMAT transmitters and receivers and wherein the ring shaped arrays of EMAT receivers are located between the ring shaped arrays of EMAT transmitters.

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Fig.1a.

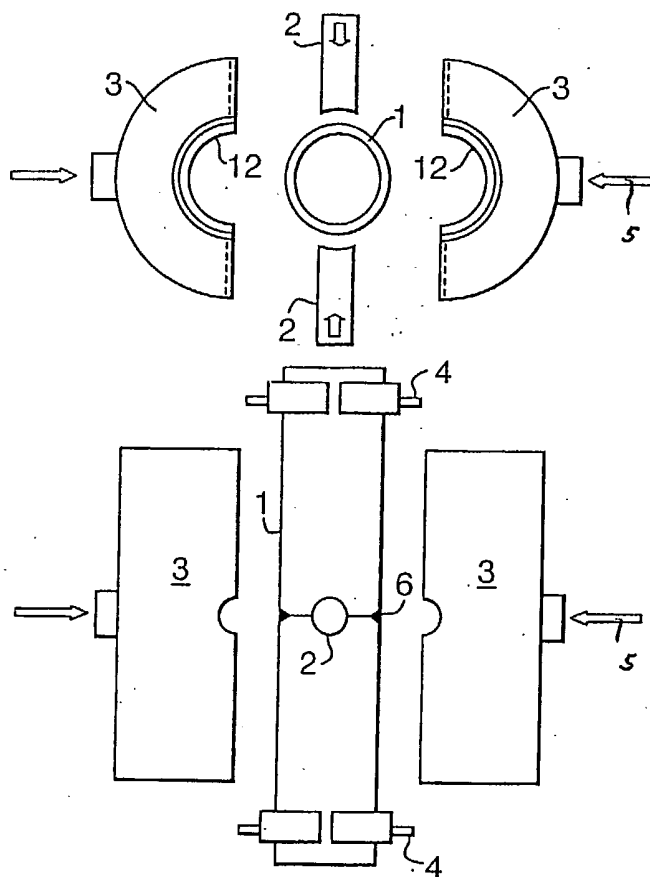
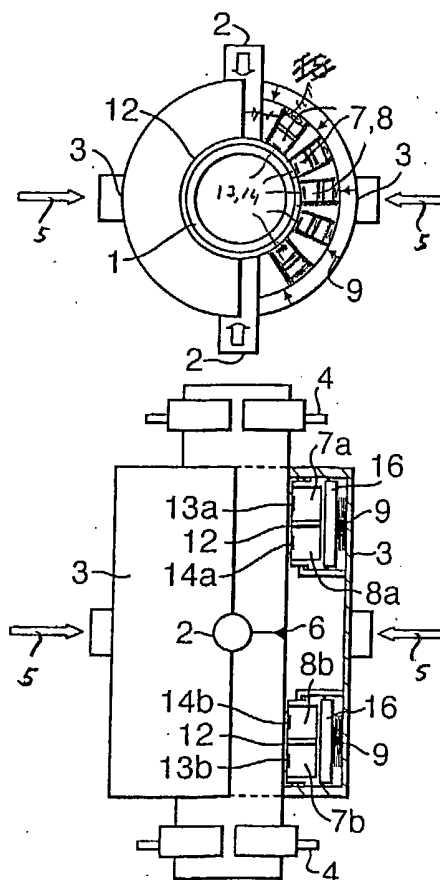


Fig.1b.



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Fig.2.

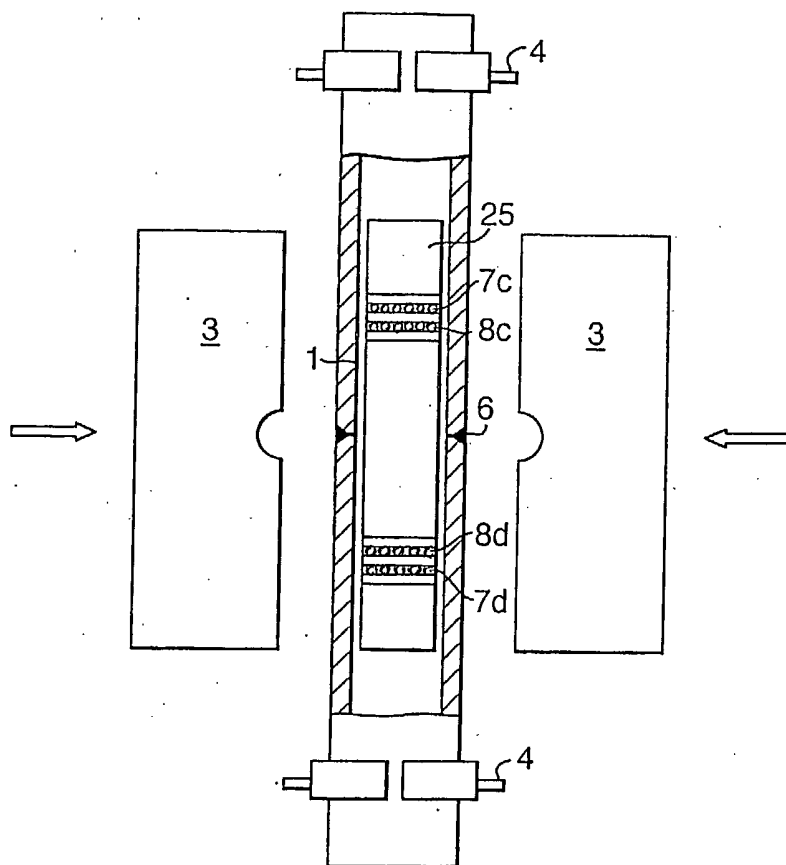
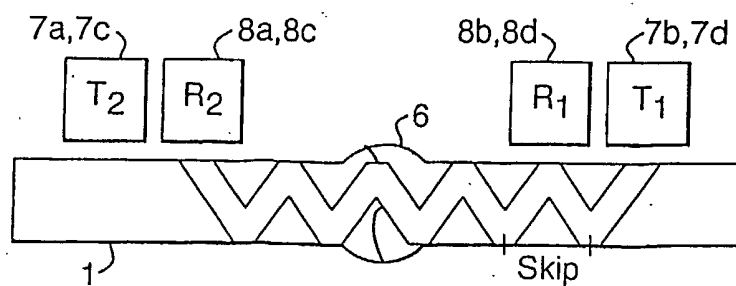


Fig.3.



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Fig.4a.

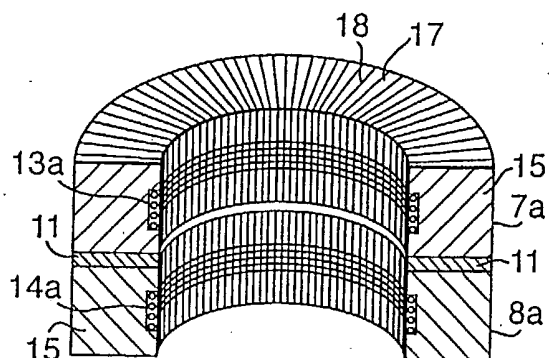


Fig.4b.

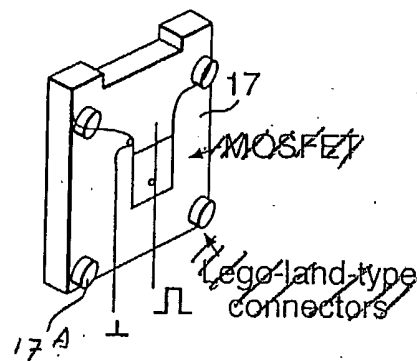


Fig.4c.

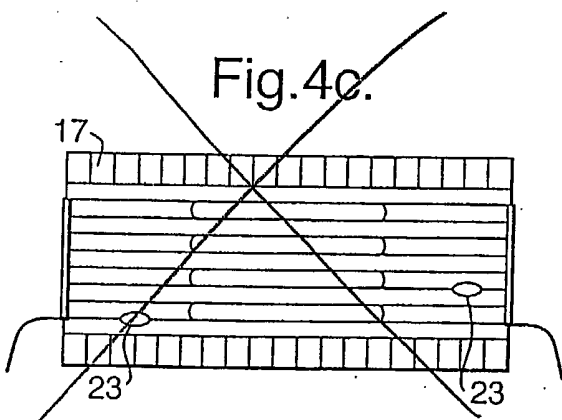


Fig.4d.

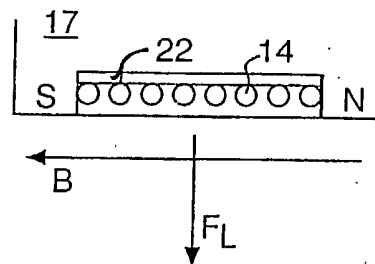


Fig.4e.

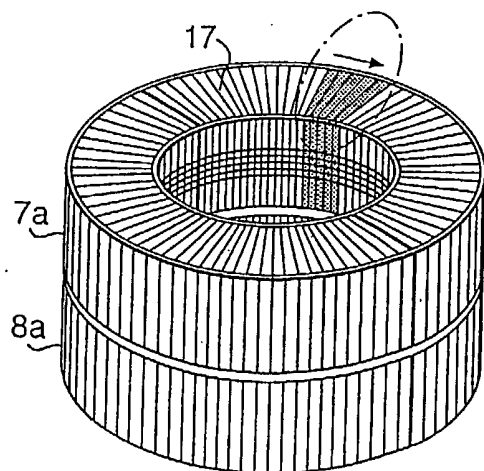
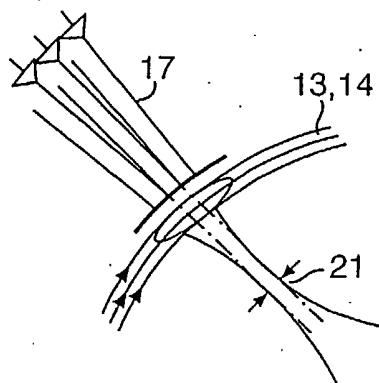
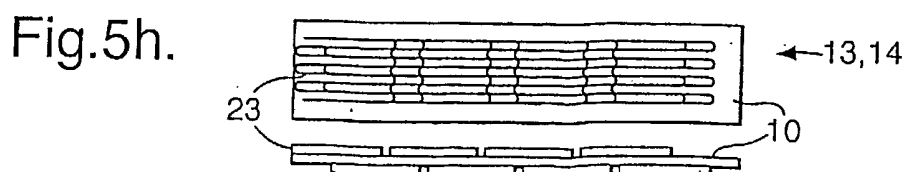
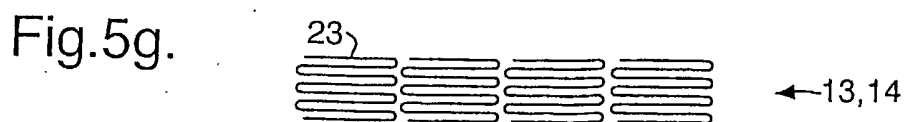
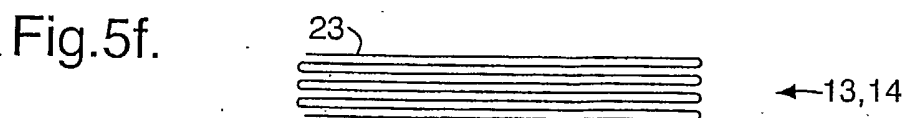
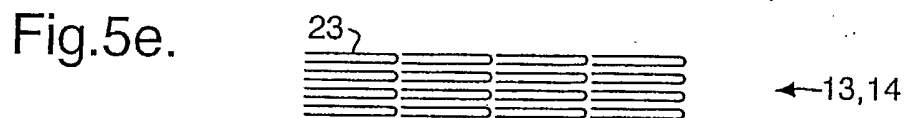
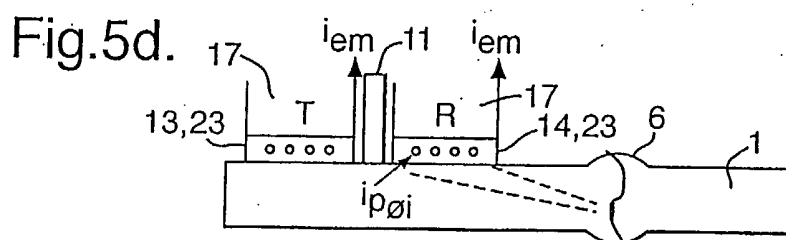
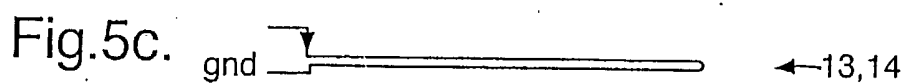
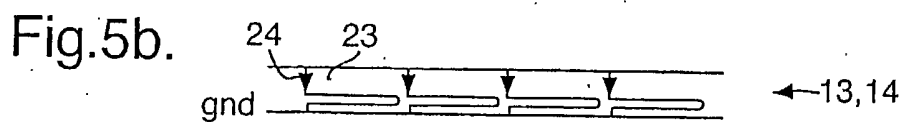
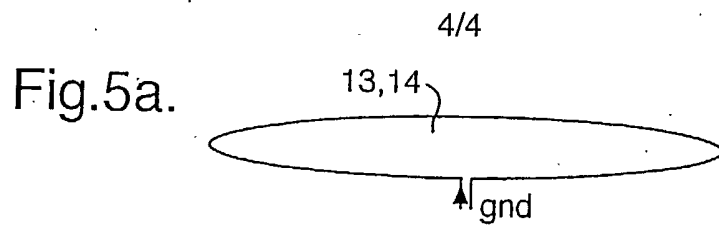


Fig.4f.





# INTERNATIONAL SEARCH REPORT

International Application No

PCT/EP 03/08053

A. CLASSIFICATION OF SUBJECT MATTER  
IPC 7 B23K31/12 G01N29/04

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 B23K G01N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the International search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, INSPEC, COMPENDEX

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

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X	the whole document	10, 11
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X	the whole document	10
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☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

11 November 2003

Date of mailing of the international search report

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## INTERNATIONAL SEARCH REPORT

International Application No.

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